

Probing magnetic fields with Square Kilometre array and its precursors

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Abstract

Origin of magnetic fields, its structure and effects on dynamical processes in stars to galaxies are not well understood. Lack of a direct probe has remained a problem for its study. The first phase of Square Kilometre Array (SKA-I), will have almost an order of magnitude higher sensitivity than the best existing radio telescope at GHz frequencies. In this contribution, we discuss specific science cases that are of interest to the Indian community concerned with astrophysical turbulence and magnetic fields. The SKA-I will allow observations of a large number of background sources with detectable polarization and measure their Faraday depths (FDs) through the Milky Way, other galaxies and their circum-galactic mediums. This will probe line-of-sight magnetic fields in these objects well and provide field configurations. Detailed comparison of observational data (e.g., pitch angles in spirals) with models which consider various processes giving rise to field amplification and maintenance (e.g., various types of dynamo models) will then be possible. Such observations will also provide the coherence scale of the fields and its random component through RM structure function. Measuring the random component is important to characterise turbulence in the medium. Observations of FDs with redshift will provide important information on magnetic field evolution as a function of redshift. The background sources could also be used to probe magnetic fields and its coherent scale in galaxy clusters and in bridges formed between interacting galaxies. Other than FDs, sensitive observations of synchrotron emission from galaxies will provide complimentary information on their magnetic field strengths in the sky plane. The core shift measurements of AGNs can provide more precise measurements of magnetic field in the sub parsec region near the black hole and its evolution. The low band of SKA-I will also be useful to study circularly polarized emission from Sun and comparing various models of field configurations with observations.

1 Introduction

Magnetic fields are detected in almost every astrophysical object in the Universe. Starting from stars like our Sun, the interstellar medium of nearby spiral galaxies and the intracluster medium of galaxy clusters, all host dynamically important magnetic fields. As a consequence, magnetic fields play a wide variety of roles ranging from controlling present day star formation where it possibly

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determines the typical masses of stars and the initial mass function, regulating the propagation and confinement of cosmic rays to the launching and maintenance of galaxy outflows. In disk galaxies, magnetic fields contribute significantly to the total pressure of the interstellar gas while outflows from galaxies control the magnitude and structure of magnetic fields in galactic halos and could be responsible for magnetising the intergalactic medium.

Magnetic fields can be probed chiefly by four techniques : (i) synchrotron emission in the radio band (both in the continuum and polarized components), which provides its field strength and orientation in the sky plane. (ii) Zeeman effect, which independently measures its strength in cold gas clouds, and (iii) Faraday rotation, which provides the line of sight averaged fields. Polarization angle provides its orientation in the sky plane. Other than the above, non-relativistic electrons in presence of magnetic fields produces (iv) cyclotron emission. Given the typical magnetic field strengths in stellar bodies, such narrow band circularly polarized emission could be detected at radio frequencies. This technique can directly yield the magnetic field strength, and is often used to study magnetic fields in Sun and other stars. On the theoretical front, conservation of magnetic helicity has now been recognised as a crucial ingredient in amplifying magnetic fields to saturated strengths (Brandenburg & Subramanian, 2005a). Nonlinear models of magnetic field evolution based on this conservation law is already in place for probing galactic magnetic fields (e.g., Shukurov et al., 2006a) and efforts are on to incorporate it in the solar context (see Charbonneau, 2014, for a review).

In spite of these important developments, our understanding of how magnetic fields are amplified and maintained in various astrophysical objects is far from clear. The 'Origin of Cosmic Magnetism' is one of the main themes of research of the upcoming Square Kilometer Array which will have a collecting area of more than an order of magnitude higher than the existing largest radio telescope (GMRT). In the first stage, referred to as SKA-I, it is envisaged to have a sensitivity of almost an order of magnitude higher ¹ than the Jansky Very Large Array (JVLA) and is expected to finish by early next decade.

Given this rapid advancement in observational progress driven by the construction of the SKA, we discuss in this article, some of the issues associated with cosmic magnetic fields which are of interest to the Indian community that we aim to address with the SKA-I.

2 Magnetic fields in galaxies

2.1 Challenges in measuring magnetic fields in galaxies

Synchrotron emission and its polarization are useful tracers of magnetic fields, but are dominantly detected in regions where the density of cosmic rays and associated relativistic electrons are relatively high (i.e., near star forming regions), or where the magnetic field is stronger. However, certain regions of interest for magnetic field studies are far from star formation regions and supernova remnants (e.g., inter-arm regions in galaxies), and these regions could have to be excluded for magnetic field studies, which could bias the results. Moreover, this method yields magnetic fields in the sky plane under the assumption of energy equipartition between cosmic rays and magnetic fields (see, e.g., Basu & Roy (2013)). However, this method suffers from assumptions of equipartition between different components of ISM and they can deviate from equipartition values in certain conditions and below certain size scales.

A much more pervasive probe of interstellar magnetic fields is by Faraday rotation. Due to this effect, magneto-ionic ISM causes the position angle of a linearly polarized wave to rotate. For

¹https://www.skatelescope.org/wp-content/uploads/2014/03/SKA-TEL-SKO-0000007_SKA1_Level_0_Science_RequirementsRev02-part-1-signed.pdf

an electromagnetic wave emitted from a source at position r , with intrinsic position angle θ_0 at a wavelength λ , the detected position angle is

$$\theta' = \theta_0 + \text{FD } \lambda^2$$

In this expression, the Faraday depth (FD), in units of rad m^{-2} , is defined by

$$\text{FD} = K \int B \cos(\phi) n_e dl$$

where $K = 0.81 \text{ rad m}^{-2} \text{ pc}^{-1} \text{ cm}^{-3} \mu\text{G}^{-1}$, B , ϕ and n_e are the magnetic field strength (in μG), inclination of the magnetic field vector to the line of sight and number density of thermal electrons (in cm^{-3}), respectively. The integral is carried out along the line of sight from source at r to the observer. When the emission originates from a single FD, it is equivalent to the Faraday rotation measure (RM). This typically happens if there is a single foreground magneto-ionic medium inducing the Faraday rotation of a background source. However, in general polarized synchrotron radiation arises from the same volume that is also inducing Faraday rotation, in which case the net polarized intensity is a superposition of the emission from various FD's with corresponding Faraday rotation. Then the observed RM (got by fitting a λ^2 law to the position angle of the polarization) will not be equivalent to a single FD.

Multi-wavelength observations of background polarized sources can directly yield the FD along the line of sight. However, even in simple cases with a single FD, it does not yield a value for B . The sign of the FD can provide information on the direction of the magnetic field. When, electron density along the line of sight is known, the mean amplitude of the magnetic field strength along the line of sight can be directly inferred. In external galaxies, electron density is frequently estimated from H_α emission. However, this is easily absorbed by dust, and extinction correction due to dusts at far-IR wavelengths is problematic due to lower resolution and sensitivity of existing observations in this band. Moreover we note here that H_α emission is dominated by clumpy ionized gas (HII regions), while the FD and the RM is dominated by the diffuse ionized gas. Thus, H_α intensity can only be used to provide a model of the electron density distribution in galaxies. Nevertheless, in the modern era, especially with the launch of Herschel, the resolution at far-IR wavelengths is approaching the resolution of radio telescopes. Reliable measurements of electron densities in external galaxies to convert FDs to a line of sight averaged value of B should then be possible in SKA-I era.

In our galaxy, pulsar dispersion measure can provide the line of sight electron density, which can be used to find an average value of B_{\parallel} from its FD (here B_{\parallel} is the line of sight magnetic field component). However, even in this case, there could be complications due to correlations between B_{\parallel} and n_e . Since these are not easily accounted for, getting accurate measurements of B_{\parallel} by this method is difficult even at higher radio frequencies where depolarization is insignificant.

2.2 Survey of background sources for polarized emission with SKA (RM grid)

As discussed above, the drawbacks of measuring magnetic fields through indirect means cannot go away with new telescope. However, SKA-I with 2 orders of magnitude of higher sensitivity than the old VLA will sample the magnetic fields in galaxies through observations of background sources much better than the existing observations. For example, with the (old) VLA, one could find measurable Faraday rotation towards only ~ 1 source per square degree with an integration time of ~ 10 minutes per source. This seriously limits the number of measurements available in a given region and affects the reliability of results derived in complex regions in the Galactic plane

(see, e.g., Roy et al. (2008)). Typical angular size of nearby (~ 10 Mpc) spiral galaxies is $\lesssim 10'$. Therefore, even with integration time of an hour per background sources, there would only be a few background sources with measurable polarization/RM seen through nearby galaxies. Therefore, deciphering magnetic field structures in these galaxies is very challenging by this method with the existing radio telescopes.

As discussed in Beck & Gaensler (2004), an appropriate observing wavelength for detecting large numbers of polarised sources is \sim GHz. This provides a large field of view, without introducing severe internal depolarization effects which will prevent FDs from being measured in many extragalactic background sources. With an angular resolution of better than $1''$, if typical extragalactic sources are polarized at $\sim 3\%$, this will allow measurable FDs towards ~ 1000 sources per square degree in the sky with an integration time of ~ 1 hour per field (assuming the field of view to be about a degree). This will allow disentangling of local FD effects from the systematic ones in our Galaxy, and allow a detailed map of magnetic fields in the Galaxy. If one observes nearby galaxies (size $\sim 10'$) with SKA-I at 1.4 GHz for ~ 1 hour, several tens of background sources with measurable FDs will be seen through them. This will reduce existing sampling bias to a large extent. To improve sensitivity of FD observations, steep spectrum of background sources need to be considered while minimising significant depolarization. SKA1-MID band 4 from 2.8-5 GHz is well suited. It provides detection of minimum FD of a few tens of rad m^{-2} and can detect FD upto about 500 rad m^{-2} (Beck et al., 2015a). Typical sensitivity would be about $0.2 \mu\text{Jy/beam}$ with integration time of 12 hour. As a caveat, we note here that most of the polarised AGN's required to measure the foreground RM have complicated internal structure (Anderson et al., 2016; Kim et al., 2016). Measuring the internal Faraday structure of these sources could require additional observations both in the lower frequency band around 1 GHz and higher frequency band (~ 8 GHz) to identify complicated internal structures in FD space. These sources may either be avoided or suitably modeled before using them as probes of the intervening medium.

2.3 Rotation measure synthesis and magnetic field tomography

Multifrequency observations of polarized sources in the past have been used exclusively to determine their RMs. A linear fitting of measured polarization angles to λ^2 was used for the above. However, the above relation is only true when there is a single compact source in the synthesised beam of a radio telescope and there is no line of sight superposition with any other Faraday screen. When there are more than one source in a telescope beam or the source is extended, the simple linear relationship of FD with λ^2 breaks down. This is due to depolarization and was first discussed in detail by Burn (1966). He also introduced a Fourier transform relationship between complex polarized surface brightness (P) and FD (ϕ). Brentjens & de Bruyn (2005) have further considered the case of limited sampling of λ^2 space and on constant emission spectrum. Many of the modern radio astronomy telescopes have large bandwidth and a large number of spectral channels across the observing band. For such cases, Fourier inversion of the measured complex polarized emission as a function of frequency channels is possible. RM synthesis by Brentjens & de Bruyn (2005) can be employed to recover the RMs of individual Faraday screens when several of them are located along the same line of sight. The λ^2 coverage of any given observations is incomplete, and a sampling function called the RM spread function (RMSF) is defined in the Faraday domain. It is also necessary to make an assumption about P for negative values of λ^2 . The Faraday spectrum can be deconvolved using RMSF through *RM CLEAN* (Heald et al., 2009). In certain situations, the technique may not work well and can be complemented by fitting in the Q, U domain (O'Sullivan et al., 2012). Longer radio wavelengths are required for a high FD resolution $\delta\phi = 2\sqrt{3}/\Delta\lambda^2$ (where, $\Delta\lambda$ is the wavelength coverage). The maximum FD that can be measured is given by $|\phi_{max}| = \sqrt{3}/\delta\lambda^2$

(where, $\delta\lambda$ is the channel width) (Brentjens & de Bruyn, 2005). Typical FD in the tomography studies varies from a few to a few hundred rad m^{-2} . This requires broad frequency coverage with the lower part of the observing band going down below 1 GHz. Observations with SKA survey band 2 from 650 MHz to 1.7 GHz would be very useful. The lowest frequency of SKA1-MID is proposed to be 950 MHz and will also be useful for the purpose. The upgraded Giant Metrewave Radio Telescope (GMRT) will also have an observing band from about 600–900 MHz along with the existing 1–1.4 GHz band. It should be possible to use these bands of GMRT to gain experience with RM synthesis before SKA1 survey band 2 is operational. We note that Ionospheric Faraday rotation causes significant problems in calibrating radio polarization data at metre wavelengths. Therefore, polarization observations at frequencies below 500 MHz could be difficult to calibrate with the GMRT for most sources (except pulsars) with weak polarized emission.

At lower frequencies, internal depolarization is present everywhere in galaxies and causes a frequency dependent modulation of the degree of polarization. Using the methodology as described above, it provides a great deal of information about the physical conditions in ISM of galaxies. Through detailed modeling of depolarization, 3-dimensional structure of the Faraday screen and magnetic fields in the ISM of galaxies can be unveiled in great details (Heald et al., 2015). This is complementary to higher frequency RM grid observations discussed earlier, which suffers little from depolarization.

2.4 Magnetic fields in the sky plane

Magnetic fields in the sky plane is not probed by the Faraday RMs described above. Synchrotron emission intensity under the assumption of energy equipartition of cosmic rays and the magnetic fields provides an estimate of the magnetic fields in the sky plane. This will provide complimentary information of what Faraday RM provides along our line of sight and is important for probing magnetic fields in galaxies which are almost face-on. In these objects, the systematic fields are likely oriented perpendicular to our line of sight (along the galactic plane). Probing magnetic fields by FD alone will fail to give complete information about these systematic fields. In radio, these fields are probed by synchrotron emission. Despite the limitation due to assumption of energy equipartition it does provide a value for the total magnetic fields in the sky plane, when the thermal emission is removed from the total emission and the synchrotron spectral index is measured. Moreover, the large scale structure of the field, and its symmetries (axi-symmetric, bi-symmetric etc.) can be constrained by observing the synchrotron polarisation angle. However, it must be noted that apart from the 'ordered' field, polarization can also be produced by an 'anisotropic' field that frequently reverses its direction incoherently. Both these types of fields may produce the same degree of polarization. A map of Faraday rotation measure (which will show large-scale coherence only for the ordered field) is therefore essential to distinguish between the two. SKA-I MID will have large bandwidths which will allow to simultaneously fit for thermal emission and spectral index of non-thermal fraction (especially between 1-1.8 GHz) across whole field of view with significant emission. Many of the spiral galaxies at distances of ~ 10 Mpc are well sampled by the present day radio telescopes like VLA and the GMRT. SKA-I with a few times better resolution and more than an order of magnitude higher sensitivity than the JVLA can easily extend the distance scale to a few times larger distance to image these galaxies. This will allow to increase the sample size by almost two orders of magnitude.

3 Scientific applications of the magnetic field measurements

3.1 Origin of magnetic fields in galaxies

There are two competing paradigms to explain the observed magnetic fields in spiral galaxies. One of them asserts that the observed structures evolved from a *primordial magnetic field* acted upon by differential rotation. The other explanation is that these magnetic fields resulted from some form of *dynamo* action by tapping the energy in turbulent fluid motions and rotational shear within the galaxy to amplify magnetic fields from *seed fields*, until the Lorentz forces back-react on the flow to saturate the field growth. Depending on the scale over which the resulting magnetic field is generated, they are classified as 'Large-scale (Mean-Field)' and 'Small-scale (Fluctuation)' dynamos. Large-scale dynamos generate magnetic fields that are spatially coherent on scales much larger than the energy carrying scale of turbulence, while fields generated by small-scale dynamos are coherent on scales on or below the energy carrying scale of turbulent motions. In stars and galaxies, these may often be both operative and then an important question is how they interact and come to terms with each other (Bhat et al., 2016).

There are however two main issues that work against the idea of a primordial origin - a) in the absence of turbulent diffusion, twisting of a primordial field by differential rotation would produce a tightly wound spiral with the field alternating on very small radial scales ~ 0.1 kpc and producing a magnetic pitch angle $p = -1^\circ$ (Shukurov, 2004), that is impossible to reconcile with the observed pitch angles of -15° (see later subsections below). The tight winding could be alleviated by turbulent diffusion expected to occur naturally in turbulent environments but then b) this would lead to the dissipation of the large-scale field on a timescale $\sim 5 \times 10^8$ yr, which is a fraction of the galactic lifetime (Shukurov, 2004; Brandenburg, 2015). In light of these difficulties it therefore seems inevitable that irrespective of the origin of the 'seed' field, some *in situ* mechanism is necessary to amplify the fields to observed strengths and sustain them over the galactic lifetime.

In this context, the *dynamo* mechanism appears to be the most promising candidate to explain the observed magnetic fields (Brandenburg & Subramanian, 2005b). Even though, the mean-field galactic dynamo theory has been able to predict some of the essential features of magnetic fields in nearby spirals (e.g., the observed quadrupolar symmetry of the regular magnetic field w.r.t the Galactic equator in the Milky Way (Frick et al., 2001)), a complete nonlinear model of the galactic dynamo taking into account the intricacies of star formation and gas dynamics is still in its infancy. We postpone a discussion of some of these issues and how we plan to address them with the SKA to the later subsections.

3.2 The Milky Way

Milky Way, due to its proximity, is an ideal test bed for studying magnetic fields in spiral galaxies. We do have detailed studies of the various constituents of the gaseous ISM in the Galaxy which could help in determining the magnetic field structure and strength. Magnetic fields in discrete objects like molecular clouds, supernova remnants, HII regions, planetary nebulae and in small scales (<10 pc) are best explored in detail in the Galaxy. Large scale reversals in arms of the Galaxy can also be studied. Our location in the Galaxy does however create difficulties in certain studies involving large angular scales (e.g., the halo).

Galactic magnetic fields are believed to be amplified and maintained by dynamos. The necessary energy could come from differential rotation of the Galaxy, turbulence in the ISM and cosmic rays. Regular fields are thought to be amplified by the mean-field alpha-omega dynamo. As discussed further in Sect. 3.5, the dynamo mode most easily excited is axisymmetric and has even parity with respect to the mid plane. The toroidal and radial component forms an axisymmetric spiral

pattern. In spherical objects, such as in galactic halos, it is expected to generate axisymmetric mode with odd vertical parity, in which the magnetic fields perpendicular to the plane pass the mid plane continuously, while the horizontal component reverses direction across the mid plane. In the disk and halo of our Galaxy, this would result in mixed-parity modes (Sokoloff & Shukurov, 1990). In presence of a Galactic wind, the mixed parity mode can be sustained (Moss et al., 2010). Apart from these simple magnetic field configurations, observations from existing sample of galaxies also show that realistic fields can have much more complicated configurations such as revealed in galaxies with a bar or in galaxies like NGC891 and NGC4565, which show an X-shaped pattern with vertical field components that increase with increasing height above and below the galactic plane and also with increasing radius. Compression and shearing by gas flows may further shape the fields and overrun the simplistic dynamo patterns predicted from theory.

As described in detail in Haverkorn et al. (2015), comparing the predictions of dynamo theory with the current observational data of the Galactic magnetic fields is still difficult. There is still uncertainty on whether the large scale field in the Galaxy is axisymmetric (Van Eck et al., 2011) or bisymmetric (Nota & Katgert, 2010). This could explain the apparent contradiction of butterfly pattern of rotation measures (RMs) in the inner Galaxy to indicating reversals of azimuthal field across the Galactic plane (Simard-Normandin & Kronberg, 1980) to lack of reversals of the field component when done locally (Frick et al., 2001). Some models of the existing observations seem to confirm the mixed parity dynamo modes (Jansson & Farrar, 2012). Characterising the global structure is, however, quite difficult due to contamination by local structures like the local magnetised bubble (Sun & Reich, 2010; Haverkorn et al., 2015).

The observations which lead to the above results are using existing RM grid observations of extragalactic sources, pulsars and diffuse synchrotron emission in the Galaxy. The models are hampered by low density of polarized sources, uncertain distance estimates of pulsars, and contamination by various discrete objects in the Galaxy. Source density is only good in the Solar neighbourhood, but cannot determine the global field structure due to insufficient data points (Stepanov et al., 2002) (see also Haverkorn et al. (2015)).

As discussed earlier, RM grid observations with SKA1-MID will yield magnetic fields every few arc-min along l and b . This will enable detailed study of magnetic fields in our Galaxy. Pulsar RM surveys with dependable distance estimate will also probe magnetic fields along many different directions. It is estimated that SKA1-LOW and SKA1-MID will discover $\sim 20,000$ pulsars in the Galaxy (Smits et al., 2011; Kramer & Stappers, 2015). This will help to model the magnetic fields in the Galaxy.

3.2.1 Turbulence in the Galaxy:

Crovisier & Dickey (1983); Green (1993) measured the power spectra of the atomic hydrogen (HI) intensity fluctuation in Milky Way, which was found to follow a power law with a power law index of 2.6 at length scales ranging a few pc to 100s of pc. These scale invariant structures have been understood to be the result of supernova driven turbulence in the ISM (Elmegreen & Scalo, 2004). Dutta et al. (2013) estimated the power spectrum of the HI intensity fluctuation from 18 external spiral galaxies. They found that the power spectra follow power laws at length scales ranging a few 100 pc to 10s of kpc with most of the galaxies having a power law index of 1.6. This dichotomy in the power law index (2.6 for Milky Way compared to 1.6 for external spirals) is understood by Dutta et al. (2009) as an effect of geometry, where at scales shorter than the scale height of the disk three dimensional structures are probed, compared to the two dimensional structures at larger scales. Owing to the lower sensitivity at high resolution their measurements were limited to > 400 pc scales. These observation raise a few questions: what drives the structures at scales of tens of

kpc and if the same mechanisms also influence the small scales structures seen in our galaxy, are these structure a result of local instabilities like the spiral arms etc.

Major inputs required to answer these questions from the observations are as follows. Investigating the link between the large scale column density fluctuations seen in external galaxies and the small scale fluctuations seen in our Galaxy needs a measurement of the power spectrum over a large range of scales. Firstly, present day observations are not deep enough such that we can probe the HI column density power spectrum over more than a decade of length scales. Moreover the baseline coverage drops significantly at larger baselines, resulting in low sensitivity at those baselines where the power spectrum signal itself is low. It has been seen that the nature of the HI velocity dispersion is significantly different inside the stellar disk of the galaxies compared to the larger galacto-centric distances (Tamburro et al., 2009). The observations also probe line of sight velocity of HI. Estimating the HI velocity fluctuation power spectrum would give us the direct measure of the energies involved in the process and hence would help us understand the generating mechanisms. A couple of visibility based estimators of the HI line of sight velocity fluctuation power spectrum are proposed (Dutta, 2016), however the present observational data lacks the required sensitivity for these measurements. SKA-I mid will have better baseline coverage and sensitivity for these power spectrum measurements. It will be possible to probe the power spectrum of HI column density selectively at different parts of the Galaxy using estimators like Tapered Gridded Estimator (Choudhuri et al., 2016).

Even though the power spectrum of the RM (RM structure function) is known, it's interpretation in terms of the magnetic field spectrum, may not be entirely straightforward. As discussed earlier, the estimate of the FD depends on the integral of the line of sight magnetic field component and the electron density. If the medium is homogeneous, the FD can be simply interpreted as an integral of the magnetic field along the sight from the source to the observer. However, densities in a realistic interstellar medium are rarely homogeneous. In that case, the estimate of the FD will depend crucially on the correlation (or anti-correlation) between n_e and $B_{||}$. There are also additional potential complications in determining the magnetic field spectrum.

Observed spectral indices of RM are much flatter than the Kolmogorov type (Haverkorn et al., 2008). Magnetohydrodynamical turbulence is also characterised by scales of energy injection and dissipation, mach number of its flow speed, and the pressure ratio of the gas to the magnetic field in plasma. Measured maximum scales of fluctuation was earlier claimed to be ~ 100 pc (Lazaryan & Shutenkov, 1990). But, more recent observations suggest a scale an order of magnitude smaller (Haverkorn et al., 2008; Iacobelli et al., 2013). The other parameters of the MHD turbulence remains uncertain (Haverkorn et al., 2015). The turbulence could be significantly driven by supernova explosions in the Galaxy, and it would imply the turbulence to be intermittent at least in small and intermediate scales in the ISM (see also Elmegreen & Scalo (2004)). Sect. 3.5 provides more details on turbulence.

3.2.2 Magnetic fields near in the central region and in discrete objects

Galactic centre (GC): Studying magnetic fields in the closest central region (~ 100 parsecs) of our Galaxy with a high resolution is important to understand the same in the central regions of similar spiral galaxies. The GC field might be the result of local effects (including any local dynamo) and accretion of matter from the rest of the Galaxy. A wind from the central region might also be required to stabilise the Galactic magnetic field configuration, and Crocker et al. (2011) found evidence for the existence of such a wind. Large uncertainties exist in determining the field strength in this region. From synchrotron emission, the estimated minimum energy magnetic field is ~ 10 μ G. However, synchrotron spectral break indicates the strength is at least ~ 50 μ G (Crocker,

2013). It is now established using the RM towards the GC magnetar that within about 0.1 pc from Sgr-A, magnetic field strength could be several mG (Eatough et al., 2013). Magnetic field strengths in dense molecular clouds vary from a fraction of a mG to several mG (Chuss et al., 2003). The structure of the magnetic fields are also unclear. Using RM grid measurements towards background sources, Roy et al. (2005, 2008) suggested the field pattern to be consistent with either bi-symmetric spiral structure or oriented along the central bar. They estimated a field strength of $\sim 20 \mu\text{G}$. However, Novak et al. (2003); Law et al. (2011) interpret the polarization in the radio synchrotron filaments as indication of a poloidal (vertical to Galactic plane) field in the diffuse ISM. The discovery of Fermi bubbles have also raised questions on their origin. They could form due to occasional formation of jets due to the central black hole, or from stellar activity in this region (Crocker et al., 2011; Carretti et al., 2013). Finding the Magnetic field structure will be important as it is likely to be linked to the maintenance of dynamo and formation of bubble like structure through stellar winds (Haverkorn et al., 2015). As discussed earlier, RM grid observations with SKA1-MID will yield magnetic fields every few arc-min along l and b . This will enable detailed study of magnetic fields in the region. Observations above 5 GHz may be more suited to avoid significant depolarization due to high RMs in the region.

Molecular clouds: Stars generally form from the collapse of molecular clouds. Magnetic fields could play an important role (Li et al., 2014) in such a process. However, due to lack of accurate measurements its role has not been properly understood. Typically, magnetic fields in clouds are measured using Zeeman splitting of HI, OH, CN lines or masers, which provides the field strength along line-of-sight. Other methods including dust induced polarization are difficult due to inherent dependency on models. An alternative method is to use the intensity of in-situ synchrotron radiation from these clouds (Orlando & Strong, 2013). Since magnetic fields in molecular clouds could be much larger than the typical ISM (Crutcher, 1999), cosmic ray electrons while penetrating inside molecular clouds should generate synchrotron emission in presence of magnetic fields (Marscher & Brown, 1978; Dickinson et al., 2015). Since cosmic ray spectrum in the Galaxy is known (Ackermann et al., 2012), and its density variation across the Galaxy has been studied, any detection will provide the total magnetic field which includes the turbulent component. Zeeman splitting is only sensitive to the regular magnetic fields. Polarized synchrotron emission could provide the ratio of regular versus the anisotropic random component (Dickinson et al., 2015). There have been many observations to detect in-situ synchrotron emission from molecular clouds (Dickinson et al., 2015), but they were not successful (Yusef-Zadeh et al., 2013, 2007). Clear detections and measuring magnetic fields in clouds allow us to infer the relative contribution of gravitational, kinetic and magnetic energy densities in dense molecular clouds. It would enable testing star formation models involving ambipolar diffusion and turbulence (Crutcher, 2012; Lazarian et al., 2012). The effective brightness temperature of molecular clouds at 408 MHz using the cosmic ray flux model has been tabulated by Dickinson et al. (2015) (see their Table-1), which shows that SKA1 would easily detect many molecular clouds through their in-situ synchrotron emission and enable measuring total magnetic fields at different parts of the clouds. The dense cores of the clouds are typically less than 0.1 pc in size, subtending an angle $\sim 1''$ at distances of the $\sim \text{kpc}$. This matches well with SKA1-MID resolution and sensitivity. Estimated flux densities of $\sim \text{mJy}$ can easily be detected at GHz frequencies.

Young stellar objects (YSOs): YSOs quite often produce jets, but the launching mechanism of these jets and the role of magnetic fields in their production is ill understood (Ray, 2009). One expects that active accretion to the central object fuels these jets, where magnetic field could provide support for stabilising the magnetised jets (Haverkorn et al., 2015). Synchrotron emission from most of these objects is quite weak, and SKA1 at frequencies of a GHz or so would be well suited to detect such faint small angular sized jet emission.

Supernova remnants (SNRs): SNRs are the main drivers of turbulence and cosmic rays in the ISM. Magnetic fields in SNRs can be enhanced to mG strengths due to shock induced compression. It is believed that magnetic fields in SNRs carry the signature of large scale Galactic magnetic fields (Kothes & Brown, 2009). There is also some evidence for toroidal fields believed to be caused by the stellar wind of the progenitor (Harvey-Smith et al., 2010). Measuring magnetic fields in a large sample of SNRs will shed light on any relationship of local Galactic magnetic fields and/or the progenitor fields in the evolution of the SNR and its magnetic fields (Haverkorn et al., 2015). A knowledge of magnetic fields in SNRs will also help to compare the radio and high energy emissions from SNRs. As discussed earlier, RM grid observations will yield magnetic fields every few arc-min along the shell of SNRs. This will enable detailed study of variation of magnetic fields around SNRs.

HII regions: Magnetic fields in HII regions are also expected to be dependent on local Galactic magnetic fields. Magnetic fields could also affect the dynamics in HII regions. Studying a large no. of such objects over a large range of densities with RM grid could unveil any such dependence.

Faraday screens: These are structures observed through polarization properties in the ISM, where no total intensity emissions could be identified (Haverkorn et al., 2003; Shukurov & Berkhuijsen, 2003). Better knowledge on their properties could arise from other studies involving polarization observations with SKA1 both through RM grid and Faraday tomography.

3.3 Nearby Galaxies:

3.3.1 Coupling of magnetic fields with ISM

The ratio of radio and far-infrared (FIR) flux density is known to be well correlated among galaxies. Radio emission in galaxies at GHz frequencies is mostly generated from non-thermal process, while the FIR emission is thermal in nature and is produced by dust. The relationship holds good over more than five orders of magnitude (Condon, 1992). The relationship also does not evolve between local galaxies to galaxies at redshift up to three (Murphy, 2009a). There are several models to explain the correlation. In the calorimeter model, young massive stars are considered as a source of IR (through reprocessing of stellar emission) and radio emission (through supernovae). However, Niklas & Beck (1997) found a tight and non-linear global correlation between gas density and magnetic fields under equipartition assumption. This correlation also holds locally in galaxies, which is explained by close coupling of gas and magnetic fields with the form $B \propto \rho_{gas}^k$ (Helou & Bicay, 1993; Thompson et al., 2006). However, the slope of the correlation varies between arm and inter-arm regions. Depending on the observing frequency in the radio band, the local correlations do not hold spatially below certain scale lengths (Basu et al., 2012). This is due to cosmic ray electron propagation during their lifetime from their origin (Basu et al., 2012). High resolution radio continuum observations in nearby galaxies are needed to identify the right model for the propagation. The ratio of the radio to FIR emission is a measure of turbulent field amplification at present in the star forming regions (Tabatabaei et al., 2013). This ratio changes depending on the star formation rate and magnetic field strengths across the disk of a galaxy (Heesen et al., 2014). High resolution sensitive observations of nearby galaxies could determine the level of turbulent field amplification in different environment (Beck et al., 2015a). Tight correlation between non-thermal radio emission and molecular line emission (CO) has also been observed for galaxy M51 (Schinnerer et al., 2013). Coupling between molecular cloud density and non-thermal emission could arise due to (i) coupling between gas density and total magnetic fields, or (ii) increased synchrotron emission from secondary cosmic ray electron produced from interaction of cosmic rays with dense molecular material (Murgia et al., 2005). However, the above observation was done

with a spatial resolution of 60 pc, and observations with higher resolution in radio with SKA1 and molecular cloud with ALMA for a larger sample of galaxies could differentiate between the above two scenarios (Beck et al., 2015a).

3.3.2 Magnetic fields in galaxy halos

Galaxies can show significant outflows to the intergalactic medium and can transport magnetic fields out of the galaxy disk (Heald, 2012). Models of galactic outflows can reproduce the available multi frequency observations only if cosmic rays and magnetic fields activate the wind at their bases in galactic bulges (Everett et al., 2008; Samui et al., 2010). Earlier galactic wind models neglected cosmic rays, but, the energy density in cosmic rays is comparable to thermal gas, magnetic fields and turbulent motion energy density in the ISM (Beck et al., 2015a). Like our Milky Way, many galaxies with moderate star formation activity and supernovae can drive a galactic wind (Breitschwerdt et al., 1991). If the wind primarily consists of hadronic particles (e.g., protons), the γ -ray emission from it will show the typical pion bump in the GeV energy range and secondary electrons produce inverse Compton scattering. However, in case the wind is driven by leptons (e.g., electrons), inverse Compton emission from primary cosmic ray electrons will dominate in the GeV to TeV range. In radio bands, the synchrotron spectrum and polarization would have certain specific signatures from any of the above two processes (Beck et al., 2015a). Radio and gamma ray observations would provide important information on the origin and propagation of the cosmic rays and the magnetic field that affects their propagation. Secondary electrons are thought to be produced in a more isotropic environments than the primary electrons, and is expected to show less polarized emission, which could be checked with sensitive SKA1 observations at GHz frequencies (Beck et al., 2015a). The Sunyaev-Zeldovich effect up scatters the cosmic microwave background photons after interactions with the particles in the wind which is detectable with sub-mm telescopes. The ratio of synchrotron to inverse scattered radiation can be used to measure the magnetic field energy in the wind (Beck et al., 2015a) particularly for the edge-on galaxies.

Cosmic ray electrons can propagate away from a galaxy by diffusion, streaming instability along magnetic field lines or by convective transport by a wind. As the electrons propagate away from their place of origin, their emission and spectrum changes with time. With high resolution observations of vertical profiles of radio emission and its spectrum, it is possible to determine the speed of cosmic ray electrons. This has been done for NGC253 (Heesen et al., 2009) and more recently for a set of 35 galaxies (Wiegert et al., 2015). The latest observations with the JVLA indicate the regions just outside the galaxies when averaged show presence of a halo of magnetic fields and cosmic rays around them. Clearly, SKA-I with an order of magnitude higher sensitivity can bring out the size and shape of such halo around each of the individual galaxies. This will allow to verify if a single model can explain the cosmic ray propagation or outflow in different galaxies, or are there multiple processes (e.g., diffusion vs streaming instability and outflow) and depending on other physical processes in galaxies, one/some of them mostly influences the propagation of cosmic rays in galaxies.

Polarization observations in nearby edge-on spirals show an X-shaped field in the halo (Krause, 2014). Dynamo model of mean magnetic fields predicts poloidal fields in the halo. As in Beck et al. (2015a), the theoretical estimate is much smaller than the measured values and this type of field structure can be created if the effects of galactic wind are included in model (Hanasz et al., 2009). RM grid observations with SKA1 can show whether the halo field is regular or composed of loops.

Shneider et al. (2014) presented a detailed calculation of the physics of depolarization of synchrotron radiation in the multi layer magneto-ionic medium in galaxies. Faraday tomography with high angular resolution, sensitivity and large bandwidth of SKA1-MID would be useful along with

RM grid to infer the morphology of the galactic magnetic field for galaxies to a distance of more than 10 Mpc with a spatial resolution of 100 pc (Heald et al., 2015).

3.3.3 Comparison of disk magnetic fields observations with theoretical models:

In the local Universe, magnetic fields have been observed in more than a dozen nearby spirals (Van Eck et al., 2015). These observations have revealed fields of several μG strengths ordered on kilo-parsec scales along with a random component with coherence scales of a few tens of parsecs (Fletcher, 2010; Beck, 2016). It is believed that dynamo model of amplification and maintenance of magnetic fields in galaxies could match the field strengths and its direction. However, strength of magnetic fields predicted from theory depends on several poorly measured galactic parameters. Compared to field strength, magnetic pitch angle, p is a readily observable quantity whose measurements in different nearby spirals can be compared with predictions from the galactic mean field dynamo theory. The pitch angle is a measure of how tightly wound the large-scale field is and is expressed as, $\tan(p) = \overline{B_r}/\overline{B_\phi}$, where $\overline{B_r}$ and $\overline{B_\phi}$ are the radial and toroidal components of the mean magnetic field, respectively. If the field is simply frozen into the gas, it will get tightly wound by the galactic differential rotation leading to very small p . On the other hand, turbulent diffusion allows the field to partially slip through the gas, but then will lead to its decay, unless a mean-field dynamo operates to maintain the large-scale magnetic field. The observed values of p are found to be larger than what is predicted from the galactic mean-field theory. For example, the pitch angles computed from the data set of Van Eck et al. (2015) have a mean value of 25° with minimum and maximum values of -8° and -48° , respectively. On the other hand, theoretical estimates from the standard $\alpha - \omega$ dynamo predicts $|p| < 15^\circ$ in the nonlinear regime. Attempts to resolve this mismatch has led several authors to explore different recipes (Chamandy & Taylor, 2015), that range from making the disk thinner, the shear smaller, assuming the kinetic α -effect to be enhanced in the spiral arms (Mestel & Subramanian, 1991; Chamandy et al., 2013), using additional helicity fluxes (Vishniac & Cho, 2001; Sur et al., 2007), incorporating mean radial flows (Moss et al., 2000) to invoking spiral shocks (Van Eck et al., 2015). However, a limitation of the existing observational data is that different galaxies have been observed with different telescopes at different resolutions and frequencies. These complications directly hamper efficient comparison between theory and observations. The problem can be alleviated by new surveys with SKA at fixed resolutions and sensitivities. On the other hand, recent developments in galactic dynamo theory where the steady state of the mean magnetic field is controlled by magnetic helicity balance (Subramanian & Brandenburg, 2006), predict that both the strength of the mean magnetic field and the pitch angle depend on the gas surface density Σ_g and the intensity of the outflow from the disk and therefore on the star formation rate (SFR) (Shukurov et al., 2006b; Van Eck et al., 2015). Such nonlinear galactic dynamo models should also strive to incorporate realistic gas flows to improve agreement with observational data. The vast sensitivity of SKA will offer a unique possibility of tracing the total star formation rate in galaxies much better than those from existing telescopes (Jarvis et al., 2015). Thus, apart from improving theoretical models, a potentially robust measurement of the star formation rate in galaxies can lead to improved observational estimates of the magnetic pitch angle in the near future.

While the total magnetic field is observed to be stronger in the material spiral arms, quite surprisingly, in most of the observed spirals, the strongest ordered fields are detected in regions in between the material arms where the gas densities and turbulence are expected to be weaker (Beck, 2016). A classic example of this are the pronounced *magnetic arms* in NGC6946. This constitutes a significant deviation from axial symmetry as one would expect the fields to be stronger in the material arms. It is rather difficult to explain such peculiar features by simply appealing to stronger

turbulence or enhanced Faraday depolarization within the spiral arms. On the other hand, the presence of such non-axisymmetric features could be indicative of non-trivial interaction between the material spiral arms and the large-scale dynamo action.

Over the years, several different explanations have been put forward to explain the high degree of coherence observed in the inter-arm regions. These range from invoking slow and fast MHD density waves in thin galactic disks (Lou & Fan, 1998) (but using very simplified configurations for the magnetic field and galaxy rotation curves), more efficient dynamo action in the inter-arm regions due to a weaker α -effect in the material arms (Moss, 1998), drift of the magnetic fields w.r.t the gaseous arms caused by spiral perturbation (Otmianowska-Mazur et al., 2002) (kinematic model neglecting back reaction of the fields on the flow), stronger turbulence in the gaseous arms due to higher star formation rate leading to the mean-field saturating at a lower level (Shukurov, 1998; Moss et al., 2013), introducing a time delay of the magnetic response in the mean-field equations (Chamandy et al., 2013), to weakening of the mean-field dynamo in the material arms by star-formation driven outflows (Chamandy et al., 2015).

Among these, the work of Chamandy et al. (2013) explores these non-axisymmetric features by including a finite time delay in response of the mean electromotive force to changes in the mean-magnetic field and small-scale turbulence in a non-linear dynamo model based on magnetic helicity balance. This leads to a phase-shift between the material and magnetic spiral arms which reproduces the kind of features observed in NGC6946. However, the non-axisymmetric components of the mean-magnetic field driven by the spiral pattern are mainly localised around the co-rotation radius.

All these different approaches indicate that our understanding about the occurrence of magnetic spiral arms is nascent, and future research directions would require a synergistic approach between theory, observations and numerical simulations. Recent work on galactic spiral structure (Dobbs et al., 2010; Quillen et al., 2011) has revealed that the spiral patterns of many galaxies appear to wind up as opposed to being rigidly rotating (as is usually assumed in galactic dynamo models). Galactic dynamo models incorporating such winding up spirals (Chamandy et al., 2014b, 2015) have led to magnetic arms spread over a wider range of radii, and so matching observations better. This suggests an interesting synergy between dynamo theory and spiral structure theory which needs to be explored further. On the observational front, detailed high resolution data of diffuse polarized emission and Faraday rotation measure (as can be obtained from SKA-mid) can help us in understanding such magnetic arms better. Moreover, as pointed by Beck et al. (2015b), the interaction between density perturbations and magnetic fields can be probed in great detail with data of neutral and ionised gas obtained from SKA1. Besides, it would also be useful to obtain constraints on the rotation curve, velocity dispersion and spiral structure from existing data.

Alternative dynamo models - There exist dynamo models based on instabilities like the Magneto-rotational instability (MRI) to explain the generation and maintenance magnetic fields in the extra stellar disk of galaxies. In an earlier work (Basu & Roy, 2013), the magnetic field energy density in the outer parts of the galaxies were found to be higher than the turbulent total gas energy density. Mean field dynamo model may not generate such fields. Sellwood & Balbus (1999) have shown that the existence of the high H I velocity dispersion in the extra stellar disk of the spiral galaxies can be produced by extraction of the energy from galactic differential rotation through magneto-hydro dynamic turbulence. If MRI causes turbulence at large galactic radii, an associated α effect may develop, and regular fields will also be seen out to such large radii (Prasad & Mangalam, 2016). A much larger sample size than discussed above will help to confirm such a conclusion. RM grid observations with SKA1-MID would be the right choice to pursue such a project.

3.4 Magnetic fields in interacting galaxies

Interaction of galaxies form bridges between them as matter flows from one system to another. This matter, if in the form of a plasma, would carry magnetic fields due to (at least partial) flux freezing. Thus magnetic bridges could be additional probes to study galactic interactions (Drzazga et al., 2011, 2012; Beck, 2016). In fact one could envisage a situation where the material bridge although present is not visible but magnetic field structures could be detected by Faraday RMs in the intergalactic space between two galaxies. This could form a new probe to detect and study galaxy-galaxy interactions. To draw generic features of interactions, one would need several systems where the interaction is detectable through enhanced FDs of background sources. Further, one needs to study the detailed structure of the magnetic fields in the interacting region. In fact the existence of possible small-scale magnetic field structures in interacting galaxies could produce both rotation of the polarization angle and depolarization. This will cause an enhancement of the FD variance, σ_{FD} , in the line of sight having intervening interacting galaxies. SKA-I would prove to be indispensable in this context. Polarised background sources seen through the interacting region will be able to probe such regions (Akahori et al., 2014a,b). Assuming two galaxies in the nearby universe separated by $\sim 20'$ and the bridge between them to have a width of $5'$, with an integration time of 1 hour with SKA-I mid, ~ 30 background sources with measurable FDs will be observed through the region. Hence, the need of finding radio sources behind these systems is almost always satisfied. Comparing their σ_{FD} with the σ_{FD} of sources seen through the surrounding regions shall detect enhanced magnetic field strength due to matter drawn from these galaxies. Further, the resolution of the SKA will be high enough to analyse the structure of the bridges.

3.5 Turbulence in the interstellar medium and galactic dynamo

In the standard $\alpha - \omega$ dynamo picture, the toroidal component of the magnetic field is generated from the radial component through differential rotation, while the radial component is regenerated from the toroidal component through the α -effect, involving helical turbulent motions in the disk. In simple terms, the growth of the large-scale fields is controlled by the dynamo control parameters, $R_\alpha = \alpha h / \eta_t$ and $R_\omega = Gh^2 / \eta_t$ characterising the intensity of induction effects due to helical turbulence and differential rotation respectively. Here h is the disk scale-height, G is the large-scale velocity shear rate, $\eta_t = ul/3$ is the turbulent magnetic diffusivity and $\alpha \simeq l^2 \Omega / h$ with l being the driving scale of interstellar turbulence and Ω is the angular velocity of rotation. Star formation in spiral galaxies, resulting in supernova explosions are the main drivers of turbulence in the ISM. Large-scale magnetic fields in galaxies are produced by motions in the diffuse, warm gas which is partially ionized. In most studies of galactic dynamos, the driving scale is chosen to be ~ 100 pc and the typical turbulent velocity, $u \sim 10 \text{ km s}^{-1}$ which is equal to the sound speed of the gas in the warm medium. However, if supernovae go off randomly in space, it is difficult to justify a particular value for the driving scale of turbulence. In fact, numerical simulations of supernovae driven turbulence in a stratified medium by Joung & Mac Low (2006) show that there is no single effective driving scale. Instead, the kinetic energy is distributed over a wide range of wave numbers. Note here that the turbulent driving scale and the turbulent velocity also determine the amplitude of the turbulent diffusivity. Moreover, both the driving scale and the turbulent velocity can vary depending on the gas surface density and the supernovae rate in the galaxy. In fact, observations by Genzel et al. (2011) and Swinbank et al. (2011) find velocity dispersions of $\sim 50 - 100 \text{ km s}^{-1}$ in high surface density disks, which could possibly arise from gravitational instabilities (Sur et al., 2016). Thus, it is crucial to make correct estimates of these quantities which in turn will provide improved estimates of the dynamo parameters. However, the nature of turbulent flows in the magnetised ISM is largely

unknown as the key properties of turbulence are poorly constrained by observations. Recent work by Gaensler et al. (2011) and Burkhart et al. (2012) has shown that the skewness and kurtosis of polarization gradients of synchrotron emission can constrain the sonic Mach number in the warm ionized medium. Correlation of the Mach number with the temperature can provide insights into the nature of the turbulent cascade in the ISM. Such techniques coupled with statistical analysis of synchrotron intensity fluctuations can provide robust estimates of the turbulent parameters in the ISM. These measurements could compliment the direct detection of turbulent velocities through observations of the redshifted 21 cm line. One will require a signal-to-noise ratio of 30, an angular resolution of about $20''$ and a sensitivity of $1 \mu\text{Jy beam}^{-1}$ (Herron et al., 2016), which can possibly be achieved with the SKA.

A concomitant issue is the spectrum of the small-scale magnetic fields which forms the turbulent component of the total magnetic field. Such fields could result from either the operation of a small-scale dynamo in the galactic ISM or from the tangling of the regular magnetic field. Both of these components give rise to synchrotron emission in the sky plane. Thus, how can one distinguish between these two types of fields observationally, in terms of their power spectra and correlation lengths? If such fields arise from small-scale dynamos, they are likely to be less volume filling compared to their tangled counter parts. However, given the limitations in spatial resolution of present day radio observations, it is difficult to clearly distinguish the typical correlation length scales, and the power spectra of these components. In fact, power spectra of a tangled magnetic field is expected to show fluctuations over a wide range of spatial scales as the magnetic field is tangled on multiple different scales. If the turbulent component of the field is generated only by small-scale dynamo action, one would expect them to be correlated on at most the scale of turbulence in the galaxy. Their presence can be identified from large fluctuations in the synchrotron emission while the turbulent component resulting from tangling of the regular field is expected to give rise to moderate levels of fluctuations in synchrotron emission. In a recent work, Houde et al. (2013) derived the degree of anisotropy in magnetic field fluctuations from the scatter in the observed polarization angles at high radio frequencies (i.e., for small Faraday rotation angles). But as pointed by Beck et al. (2015b), this technique is now restricted to only a few bright patches of polarization seen at the highest possible resolution in M51 with the correlation lengths parallel and perpendicular to the local ordered field being about 100 and 50 pc respectively.

Given the high spatial resolution offered by the SKA, it would become possible to resolve these issues through polarization observations at spatial resolutions of 1 – 100 pc. Moreover, improved Faraday depolarization measurements may also shed valuable information on the correlation scale.

3.6 Probing magnetic fields at high redshifts

MgII absorption systems probed by Bernet et al. (2008, 2010); Farnes et al. (2014) also reveal the existence of magnetic fields in galaxies at redshifts $z \sim 1$. These fields are of comparable strengths to those that are observed in galaxies of today. This raises the interesting question of how such strong magnetic fields are generated at early epochs and how such fields evolve in redshift along with the evolution of the galaxy itself. Specific predictions about magnetic fields in young galaxies were presented in Arshakian et al. (2009) and Schleicher & Beck (2013). In the context of hierarchical galaxy formation, magnetic fields have been considered by Rodrigues et al. (2015). Detailed study of field evolution at high redshift requires one to explore how major mergers, star-formation rate (SFR) etc. influence the gradual evolution of magnetic fields with time. While the fields in these galaxies may not have had the time to get ordered on larger scales (i.e., on scales bigger than the scale of turbulence), they can nevertheless be detected via their resulting synchrotron emission. However, while energy losses of cosmic ray electrons due to inverse Compton scattering off CMB

photons are negligible in the local Universe, the rapid increase of the CMB energy density by a factor $\sim (1+z)^4$ indicates that at high redshifts, such losses will become dominant compared to losses due to synchrotron radiation (Murphy, 2009b). This in turn will make it difficult to observe galaxies in radio beyond a certain critical redshift. Deep imaging capabilities of SKA-I mid at GHz frequencies can be used to probe the polarization properties of galaxies at high redshifts. In particular, SKA-I is expected to detect ~ 5000 galaxies per square degree above 10σ , which implies that it can probe magnetic fields in $\sim 50,000$ galaxies out to redshift $z > 4$ for a 10 square degree survey (Taylor et al., 2015). This will allow to test different models which could generate magnetic fields in short timescale.

These include (i) fluctuation dynamos, (ii) quasi-linear global dynamo models with specific radial forms for diffusivity and alpha effect, (iii) models which treat growth of fluctuations and mean in a unified manner (Bhat et al., 2016). Fluctuation dynamos, appear to be a suitable candidate capable of rapid amplification of magnetic fields on the eddy-turnover-time scale, much shorter than the lifetime of a galaxy (Brandenburg & Subramanian, 2005a). They also can lead to sufficiently coherent fields to explain the observations (Bhat & Subramanian, 2013). Such dynamos can also generate fields much before the formation of the disk by tapping into the energy in the turbulent motions of the halo gas as the galaxy forms (Sur et al., 2010, 2012).

Mean field models with helicity fluxes can avoid catastrophic quenching of the dynamo, and the simplest example of such a flux arises from advection of the field through galactic outflows (Shukurov et al., 2006b). In the case of quasi-linear dynamo model (Prasad & Mangalam, 2016), a global axisymmetric turbulent dynamo operates in a galaxy with a corona. It treats the supernovae (SNe) and magneto-rotational instability (MRI) driven turbulence parameters under a common formalism where the diffusivity and alpha effect have radial variation as the shear. The nonlinear quenching of the dynamo is alleviated by inclusion of small-scale advective and diffusive magnetic helicity fluxes (eg. Sur et al. (2007), Chamandy et al. (2014a)), which allow the gauge invariant magnetic helicity to be transferred outside the disc and consequently build up a corona (halo) during the course of dynamo action. The quadrupolar large-scale magnetic field in the disc is found to reach equipartition strength within a timescale of 1 Gyr which is much smaller than those predicted by other models. The large-scale magnetic field in the corona obtained is much weaker in strength compared to the field inside the disc and has only a weak impact on the dynamo operation.

The structure and strength of the coronal magnetic field is one important discriminant. Also, observations of the galactic magnetic field strength at different redshifts is key to understanding the timescale of saturation of the dynamo. In addition the magnetic pitch angle obtained by this model can be compared with observed values.

4 Magnetic fields in galaxy clusters

Galaxy clusters are found to be magnetised and these fields are important in understanding the physical processes in the intra cluster medium is also recognised. Several large scale (few Mpc) features from the clusters have already been detected (Bagchi et al., 2002) with surface brightness of the order of few tens of $\mu\text{Jy}/\text{arc-sec}^2$ at 1.4 GHz. Central region of clusters often host diffuse radio halos of non thermal synchrotron emission (Govoni & Feretti, 2004) with intensity strongly correlated with the X-ray luminosity, and hence the mass of the cluster. Recent simulations of Govoni et al. (2013) suggest that the halos have intrinsically polarized emission which can be traced when observed at high resolutions (100 pc or lower). SKA1-Mid at 1.4 GHz with a resolution of about 0.2 arc sec would have the right polarisation sensitivity to observe these in many clusters (Giovannini et al., 2015).

While synchrotron radiation traces the component of the magnetic field perpendicular to the line of sight of observation, RM synthesis traces the line of sight component. Using models of the magnetic fields it has been shown that this technique can be used against background radio galaxies for clusters with mass $> 10^{13} M_{\odot}$ (Bonafede et al., 2015). Moreover, this method would be effective in probing the compressed magnetic fields at the shock fronts from the merging clusters. Johnston-Hollitt et al. (2015) outlined a technique to investigate the evolution of the intra cluster magnetic fields over cosmic time using their imprint on the tailed radio galaxies. Probing details in the morphology of the tails require high sensitivity and resolution.

Magnetic fields in clusters are possibly generated by the Fluctuation dynamo which amplifies magnetic fields on the fast eddy-turnover time scales and on coherence lengths smaller than the outer scale of turbulence. A crucial issue in fluctuation dynamos is the degree of coherence of the field in the saturated state. A recent study of directly measuring the RM from simulations of the fluctuation dynamos does seem to indicate the generated fields are coherent enough (Bhat & Subramanian, 2013). The SKA will enable the detection of many more polarized sources through an individual cluster and thus map the random field in it. One would also detect many more radio halos. In particular the enhanced sensitivity and improved angular resolution of SKA will allow one to detect polarization, which has been seen in very few radio halos at present (Govoni et al., 2015). The use of a wide bandwidth could also allow one to do RM synthesis and infer the 3-d structure of the magnetic field. The detailed mapping of the continuum emission including its fluctuations will also probe the coherence properties of the magnetic field and the cosmic ray electrons.

Away from the cluster cores, we have very little information at present about the magnetic field strength and their distribution in the cosmic web, particularly in the intergalactic filaments. Magnetic fields in filaments can be amplified by vorticity and turbulence resulting from structure formation shocks (Ryu et al., 2008, 2012; Iapichino et al., 2011). On the observational front, apart from faint radio emission observed in the outskirts of clusters (Kim et al., 1989), there is no confirmed detection of synchrotron emission and RM from filaments. Based on the observed limit of RMs of background quasars, Ryu et al. (1998) and Xu et al. (2006) inferred an upper limit of $\sim 0.1 \mu\text{G}$ for the magnetic field strength in filaments. With the growth of computing power and availability of sophisticated numerical algorithms, it has now been possible to perform cosmological MHD simulations of large-scale structure formation including the formation of galaxy clusters. A major drawback of these simulations is their inadequate resolution to resolve the turbulent eddy scale in filaments. This makes it difficult to reach firm conclusions regarding the degree of turbulence required to amplify the magnetic fields and whether the fields in the filaments are in equipartition or are still evolving. Moreover, the field amplification is found to depend on the numerical resolution as well as on the distribution of solenoidal or compressive modes of the underlying turbulence (Xu et al., 2012; Vazza et al., 2014). Nevertheless, they offer a useful first hand estimate of the magnetic field strengths in the intergalactic filaments.

An interesting approach adopted by Ryu et al. (2008) combined the estimated levels of resulting turbulence in a large-scale structure simulation with the magnetic field growth due to fluctuation dynamos obtained from a separate three-dimensional incompressible simulation of driven turbulence. This gives an estimate of the magnetic field of tens of nG in these filaments and their RM contribution to be $\sim 1 \text{ rad m}^{-2}$. Again, the crucial question is the degree of coherence of the field. Apart from the fact that measuring RMs in these filaments are beyond the reach of current observational facilities, one is also confronted by difficulties arising out of separating RM contribution due to other sources of Faraday rotation along the line of sight (LOS). These include FDs arising from : other background extragalactic radio sources, other intervening galaxies that may lie along the LOS, the magnetic field in our Milky Way and RMs associated with the earth's ionosphere. The contribution to the RM from these sources are not negligible compared to the FDs expected from the

magnetic field in the filaments. Thus, one has to devise a clever way of separating the FD contribution from these other sources from the RMs arising solely from filaments and large-scale structure. In this context, new statistical techniques such as in Akahori et al. (2014a), Faraday tomography measurements (Akahori et al., 2014b) and measuring both the dispersion measure (DM) and FD of extragalactic linearly polarized fast radio bursts (Akahori et al., 2016) hold promise for unravelling the strength and FDs of magnetic fields in filaments with the SKA. Again as pointed out earlier, the complicated internal polarization structure of the background AGN's need to be understood (Anderson et al., 2016; Kim et al., 2016), before being able to measure the RM contribution from the IGM. On the theoretical front, the key challenge lies in understanding the saturation process of the fluctuation dynamo, for which higher resolution simulations with high fluid and magnetic Reynolds number at magnetic Prandtl number $P_m \gg 1$ are needed.

5 Magnetic fields in AGN parsec scale jets: implications for black hole physics

Blazars are core dominated Active Galactic Nuclei (AGNs) and are characterised with luminous core, rapid variability over entire electro magnetic (EM) spectra, high radio to optical polarization, superluminal motion, non thermal emission and a doppler boosted relativistic jet pointing $\leq 10^\circ$ with the line of sight (LOS). Core-jet morphology is common characteristic of most of the Active Galactic Nuclei (AGNs) in very long baseline interferometry (VLBI) images, where core is the optically thick base of the jet (Blandford & Königl, 1979) with its absolute position being the surface in the continuous flow where optical depth becomes ~ 1 (also known as 'photosphere').

According to Königl (1981), absolute position of the VLBI core moves increasingly outwards along the relativistic jet with higher wavelength which can be attributed to the synchrotron self absorption process (SSA), calling this effect as frequency dependent core shift. In the conical jet model, the VLBI core is a compact, stationary, bright and flat spectrum feature lying at one end of the jet of a typical blazar on sub-milliarcsecond (pc) scale from where super luminal components emerge and separate which appear as propagating disturbances such as shock waves (Blandford & Königl, 1979). In case of blazars the spectra of the cores at centimetre wavelength indicates core is partially optically thick to the synchrotron self absorption since their slope is ≤ 1 , which can be attributed to magnetic field and the relativistic electron density gradients.

High precision core shift measurements that can be done with VLBI involving SKA with other large area telescopes can prove to be very fruitful as it can potentially provide information on the physical parameters of the VLBI jet, like core magnetic field, distance from the core to the base of the jet (Lobanov, 1998; Hirovani, 2005), spectral index, construction of rotation measure maps, and nature of the absorbing material with SSA being dominant in the jet plasma while free free absorption driving the thermal plasma surrounding the jet in the sources viewed at large angle to the line of sight (LOS). There are several ways to measure apparent core-shifts. One of them is the phase referencing experiment where the telescope is switched between the target source and the phase calibrator (some nearby reference source) with shorter switching time as compared to the coherence time (Guirado et al., 1995; Marcaide & Shapiro, 1984; Lara et al., 1994; Bietenholz et al., 2004). A new technique is used for extracting core shifts along with other physical parameters of jet using frequency dependent time lags for single dish observations (Mohan et al. (2015); Agarwal et al. in preparation). The core-shift effect is used effectively to probe the region close to the jet launching region by a synchrotron opacity model. Applying the model to multi-band observations (4.8 GHz - 36.8 GHz) including high resolution VLBI images and light curves, they obtain the component kinematics and in the context of the core-shift effect, to constrain the core radius, magnetic field

strength (core and at pc-scales), core offset position and jet luminosity, assuming a steady conical jet affected by core brightening (flares) and associated component ejection.

Magnetic fields are expected to play a prominent role in structuring the accretion flow, the disk-jet connection, and the collimated outflow at the sub-pc to pc-scales and in possible helical signatures at the kpc-scales. Further, using the derived field strength and jet luminosity one can explore electrodynamical and hybrid jet models and place constraints on the spin and mass of the black hole. Zamaninasab et al. (2014) considered the samples of blazars and radio galaxies of and obtained core shift and magnetic field strengths. Theoretical results for equipartition and the jet opening angles can be tested. Zamaninasab et al. (2014) considered the model of jet formation from black hole (BH) spin-energy extraction (Blandford & Znajek, 1977). Zdziarski et al. (2015) considered models with the accretion being magnetically arrested (MAD; Narayan et al. (2003)). Such flows have dragged so much magnetic flux to the BH that the flux, Φ_{BH} becomes dynamically important and obstructs the accretion, $\Phi_{BH} \simeq 50(\dot{M}c)^{1/2} = 10^{-4}M_8^{3/2}\dot{m}^{1/2} \text{ pc}^2 \text{ G}$ (Tchekhovskoy et al., 2011; McKinney et al., 2012) where the accretion rate is given in units of the Eddington rate. Further, using the derived field strength and jet luminosity one can explore other electrodynamical and hybrid jet models and place constraints on the spin and mass of the black hole. SKA as part of a VLBI network with long baselines can provide key and unique contributions to the problem:

1. by verifying the theoretical SSA model using high resolution maps on sub pc scales and the determination of the optical depth as a function of radius is key to measuring the magnetic fields.
2. by spanning the range 50 MHz to 14 GHz and monitoring these AGNs for several years, we will be able to broaden the scope for such studies and offer a sizable sample for statistical and comparative studies of jet kinematics and energetics at the pc-scale which can serve as crucial inputs to fully relativistic Radiation MHD numerical simulations.
3. by going deeper in redshift, exploiting the higher sensitivity has important cosmological implications for evolution of magnetic fields in these AGNs

6 Radio observations of Solar magnetic fields

Solar coronal magnetic field can be effectively estimated using low frequency radio observations (< 150 MHz or so) in the cross-correlation mode between signals received by two mutually orthogonal dipole antennas (Sastry, 2009). It is only the circularly polarized radio emission that is observed since linearly polarized radio emission averages to zero over typical observing bandwidths at low frequencies.

Presently such observations are carried out in India at the Gauribidanur observatory with an one-dimensional array of antennas on an east-west baseline. Several interesting results on the coronal magnetic field (particularly when there is a coronal mass ejection) in the heliocentric distance range $\sim 1.2 - 2.0$ solar radii have been obtained (Ramesh et al., 2010). Large antenna arrays like SKA are expected to be more useful in this regard since:

- The higher angular resolution will help to locate the radio wave emitting source regions unambiguously. This will facilitate comparison with observations at other wavelength bands in the spectrum, both laterally and radially. Note that simultaneous observations at different frequencies help to derive the radial variation of the field strength.

- The larger collecting area (and hence better sensitivity) will help to observe faint radio emission. Such observations will be useful to estimate the coronal magnetic field associated with weak energy releases in the solar atmosphere. Radio emission from background corona can also be probed to infer the general magnetic field there.

Given this we consider two specific proposals below.

6.1 Topological properties of solar coronal fields derived from nonlinear force-free (NLFF) magnetic field solutions

Prasad et al. (2014) conducted a systematic study of force-free field equation for simple axisymmetric configurations in spherical geometry. The condition of separability of solutions in radial and angular variables leads to two classes of solutions: linear and non-linear force-free fields. They have studied these linear solutions and extended the non-linear solutions to the irreducible rational form $n = p/q$, which is allowed for all cases of odd p and to cases of $q > p$ for even p . They have further calculated their energies and relative helicities for magnetic field configurations in finite and infinite shell geometries. They demonstrate a method to be used to fit observed solar magnetograms as well as to provide good exact input fields for testing other numerical codes used in reconstruction on the non-linear force-free fields. They have further calculated their energies and relative helicities for these magnetic field configurations in finite and infinite shell geometries. This method can provide useful reconstruction of the non-linear force-free fields as well as reasonably good input fields for other numerical techniques. Observations of the solar magnetic fields by SKA can be used inputs to test the solutions and the predicted topologies. A set of solutions including pressure obtained by solving the Grad Shafranov can also be tested: self-similar solutions with twist (Osherovich, 1982), non-self similar without twist (Low, 1975a,b) and more generally with twist (Sen & Mangalam, in preparation).

6.2 Energy distribution of braided fields in Sun derived from NLFFF solutions

Observations of solar coronal loops reveal highly regular structures. It is expected that random rotations and random walk of the foot points at the photosphere twist and braid the field lines, then how can the random processes existing in corona lead to such well organised structures? Several observations have reported evidence of such braiding of magnetic field lines. It is possible that the magnetic re-connection within the loop and with other loops disentangle the field through nanoflares or microflares. The coronal field then reorganises itself through a Taylor like relaxation process to attain a force-free field configuration. It is useful and important to study this reorganisation process of a highly braided field to a force-free field geometry. The idea of crossing numbers and similar topological constructions are used to calculate the free energy content in braiding in the field lines which allows estimates of the energy released in flares from these structures. In a paper in preparation, Prasad & Mangalam (2016) test the statistical model of self-organised criticality using their nonlinear force-free field (NLFFF) solutions to find the distribution function of crossing numbers and the power law in the energy distribution of flares. Their results are in good agreement with those predicted in the model by Prasad & Mangalam (2013); Prasad et al. (2014). Further observations by SKA on the flare distribution energies and more detailed estimates of the geometry of the braided structure will be directly relevant predictions of these models.

Conclusions

Having broadly discussed the various topics of interest to the Indian community, we summarise here the specific objectives of our group which includes but is not limited to the following science cases :

1. RM grid observations of sources through some of the discrete objects in the Galaxy including the GC region, molecular clouds and SNRs (Sect. 3.2.2) to understand and model the magnetic field distribution in these objects and compare the effect of large scale magnetic fields in these objects.
2. As discussed in Sect. 3.3.1, observing a set of spirals in high resolution to model the propagation of cosmic rays along the plane and to study its correlation with emission in other bands to determine the coupling of magnetic fields with other constituents of the ISM.
3. Observe a set of nearby spirals (Sect. 3.3.2) with large bandwidths in polarization to determine and model the halo magnetic fields. Before the SKA survey band 2 is operational, we also plan to use the 0.6–0.9 and 1.0–1.4 GHz bands of GMRT to carry out RM synthesis observations of some of the nearby galaxies.
4. Comparing magnetic field observations of disk galaxies with theoretical predictions (Sect. 3.3.3) - improving agreement with observations in the values of the magnetic pitch angles and also improving our understanding of non-trivial interactions between material spiral arms and large-scale dynamo action.
5. Probe interacting galaxies and the enhanced magnetic field strength (due to the matter drawn in from these galaxies), by carrying out the comparison of the variance of the Faraday depth, σ_{FD} , of radio sources sample with and without these intervening interacting galaxies along their line of sight (e.g Sect 3.4).
6. Nature of turbulent flows in the magnetised ISM (Sect 3.5) is largely unknown as crucial properties of turbulence are poorly constrained at present. Statistical analysis of synchrotron intensity fluctuations as already reported by a number of authors, along with direct detection of turbulent velocities through observations of the redshifted 21-cm line can provide robust estimates of the turbulent parameters in the ISM. These estimates can then be incorporated into nonlinear galactic dynamo models to provide more insights into the evolution of large-scale magnetic fields in galaxies.
7. Probing the evolution of cosmic magnetic fields from high redshifts (Sect. 3.6) to the present through both new observations and improved theoretical predictions for SKA and its precursors.
8. Probing the degree of coherence of the magnetic field in galaxy clusters. In particular, the use of wide bandwidth will allow one to do RM synthesis and infer the three-dimensional structure of the magnetic field. Also, the detailed mapping of the continuum emission will be helpful to probe the degree of coherence of the magnetic field.
9. By studying the core-shift as a function of frequency over larger frequency and dynamic range in radio map,s SKA can probe magnetic fields, kinematics and spectral distribution which are key inputs to the synchrotron self-absorption models, radiation MHD simulations and black hole spin and mass estimates based on GRMHD calculations (section 5). Monitoring several

sources for several years provides cosmological evolution of sub pc properties such as magnetic field evolution and kinematics which are important clues to jet physics in these sources.

10. Magnetic configurations on the Sun extending from the photosphere to the corona can be studied and force-free and more general models can be tested (section 6.1). Furthermore observations by SKA on the flare energy distribution and the geometry of the braided structure will be directly relevant to predictions of the model based on braiding topologies and magnetic reconnections leading to nano flares (section 6.2).

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References

- Ackermann, M., Ajello, M., Allafort, A., Atwood, W. B., Baldini, L., Barbiellini, G., Bastieri, D., Bechtol, K., Bellazzini, R., Berenji, B., Blandford, R. D., Bloom, E. D., Bonamente, E., Borgland, A. W., Bouvier, A., Bregeon, J., Brigida, M., Bruel, P., Buehler, R., Buson, S., Caliandro, G. A., Cameron, R. A., Caraveo, P. A., Casandjian, J. M., Cecchi, C., Charles, E., Chekhtman, A., Cheung, C. C., Chiang, J., Ciprini, S., Claus, R., Cohen-Tanugi, J., Conrad, J., Cutini, S., de Angelis, A., de Palma, F., Dermer, C. D., Digel, S. W., Do Couto E Silva, E., Drell, P. S., Drlica-Wagner, A., Favuzzi, C., Fegan, S. J., Ferrara, E. C., Focke, W. B., Fortin, P., Fukazawa, Y., Funk, S., Fusco, P., Gargano, F., Gasparrini, D., Germani, S., Giglietto, N., Giommi, P., Giordano, F., Giroletti, M., Glanzman, T., Godfrey, G., Grenier, I. A., Grove, J. E., Guiriec, S., Gustafsson, M., Hadasch, D., Harding, A. K., Hayashida, M., Hughes, R. E., Jóhannesson, G., Johnson, A. S., Kamae, T., Katagiri, H., Kataoka, J., Knödseder, J., Kuss, M., Lande, J., Latronico, L., Lemoine-Goumard, M., Llena Garde, M., Longo, F., Loparco, F., Lovellette, M. N., Lubrano, P., Madejski, G. M., Mazziotta, M. N., McEnery, J. E., Michelson, P. F., Mitthumsiri, W., Mizuno, T., Moiseev, A. A., Monte, C., Monzani, M. E., Morselli, A., Moskalenko, I. V., Murgia, S., Nakamori, T., Nolan, P. L., Norris, J. P., Nuss, E., Ohno, M., Ohsugi, T., Okumura, A., Omodei, N., Orlando, E., Ormes, J. F., Ozaki, M., Paneque, D., Parent, D., Pesce-Rollins, M., Pierbattista, M., Piron, F., Pivato, G., Porter, T. A., Rainò, S., Rando, R., Razzano, M., Razzaque, S., Reimer, A., Reimer, O., Reposeur, T., Ritz, S., Romani, R. W., Roth, M., Sadrozinski, H. F.-W., Sbarra, C., Schalk, T. L., Sgrò, C., Siskind, E. J., Spandre, G., Spinelli, P., Strong, A. W., Takahashi, H., Takahashi, T., Tanaka, T., Thayer, J. G., Thayer, J. B., Tibaldo, L., Tinivella, M., Torres, D. F., Tosti, G., Troja, E., Uchiyama, Y., Usher, T. L., Vandenbroucke, J., Vasileiou, V., Vianello, G., Vitale, V., Waite, A. P., Winer, B. L., Wood, K. S., Wood, M., Yang, Z., & Zimmer, S. 2012, *Physical Review Letters*, 108, 011103
- Akahori, T., Gaensler, B. M., & Ryu, D. 2014a, *ApJ*, 790, 123
- Akahori, T., Kumazaki, K., Takahashi, K., & Ryu, D. 2014b, *PASJ*, 66, 65
- Akahori, T., Ryu, D., & Gaensler, B. M. 2016, *ApJ*, 824, 105
- Anderson, C. S., Gaensler, B. M., & Feain, I. J. 2016, *ApJ*, 825, 59

- Arshakian, T. G., Beck, R., Krause, M., & Sokoloff, D. 2009, *A&A*, 494, 21
- Bagchi, J., Enßlin, T. A., Miniati, F., Stalin, C. S., Singh, M., Raychaudhury, S., & Humeshkar, N. B. 2002, *NewA*, 7, 249
- Basu, A., & Roy, S. 2013, *MNRAS*, 433, 1675
- Basu, A., Roy, S., & Mitra, D. 2012, *ApJ*, 756, 141
- Beck, R. 2016, *A&A Rev.*, 24, 4
- Beck, R., Bomans, D., Colafrancesco, S., Dettmar, R. J., Ferrière, K., Fletcher, A., Heald, G., Heesen, V., Horellou, C., Krause, M., Lou, Y. Q., Mao, S. A., Paladino, R., Schinnerer, E., Sokoloff, D., Stil, J., & Tabatabaei, F. 2015a, *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, 94
- . 2015b, *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, 94
- Beck, R., & Gaensler, B. M. 2004, *NewAR*, 48, 1289
- Bernet, M. L., Miniati, F., & Lilly, S. J. 2010, *ApJ*, 711, 380
- Bernet, M. L., Miniati, F., Lilly, S. J., Kronberg, P. P., & Dessauges-Zavadsky, M. 2008, *Nature*, 454, 302
- Bhat, P., & Subramanian, K. 2013, *MNRAS*, 429, 2469
- Bhat, P., Subramanian, K., & Brandenburg, A. 2016, *MNRAS*, 461, 240
- Bietenholz, M. F., Bartel, N., & Rupen, M. P. 2004, *ApJ*, 615, 173
- Blandford, R. D., & Königl, A. 1979, *ApJ*, 232, 34
- Blandford, R. D., & Znajek, R. L. 1977, *MNRAS*, 179, 433
- Bonafede, A., Vazza, F., Brüggén, M., Akahori, T., Carretti, E., Colafrancesco, S., Feretti, L., Ferrari, C., Giovannini, G., Govoni, F., Johnston-Hollitt, M., Murgia, M., Scaife, A., Vacca, V., Govoni, F., Rudnick, L., & Scaife, A. 2015, *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, 95
- Brandenburg, A. 2015, in *Astrophysics and Space Science Library*, Vol. 407, *Magnetic Fields in Diffuse Media*, ed. A. Lazarian, E. M. de Gouveia Dal Pino, & C. Melioli, 529
- Brandenburg, A., & Subramanian, K. 2005a, *Phys. Rep.*, 417, 1
- . 2005b, *Phys. Rep.*, 417, 1
- Breitschwerdt, D., McKenzie, J. F., & Voelk, H. J. 1991, *A&A*, 245, 79
- Brentjens, M. A., & de Bruyn, A. G. 2005, *A&A*, 441, 1217
- Burkhart, B., Lazarian, A., & Gaensler, B. M. 2012, *ApJ*, 749, 145
- Burn, B. J. 1966, *MNRAS*, 133, 67

- Carretti, E., Crocker, R. M., Staveley-Smith, L., Haverkorn, M., Purcell, C., Gaensler, B. M., Bernardi, G., Kesteven, M. J., & Poppi, S. 2013, *Nature*, 493, 66
- Chamandy, L., Shukurov, A., & Subramanian, K. 2015, *MNRAS*, 446, L6
- Chamandy, L., Shukurov, A., Subramanian, K., & Stoker, K. 2014a, *MNRAS*, 443, 1867
- Chamandy, L., Subramanian, K., & Quillen, A. 2014b, *MNRAS*, 437, 562
- Chamandy, L., Subramanian, K., & Shukurov, A. 2013, *MNRAS*, 428, 3569
- Chamandy, L., & Taylor, A. R. 2015, *ApJ*, 808, 28
- Charbonneau, P. 2014, *ARA&A*, 52, 251
- Choudhuri, S., Bharadwaj, S., Roy, N., Ghosh, A., & Ali, S. S. 2016, *MNRAS*, 459, 151
- Chuss, D. T., Davidson, J. A., Dotson, J. L., Dowell, C. D., Hildebrand, R. H., Novak, G., & Vaillancourt, J. E. 2003, *ApJ*, 599, 1116
- Condon, J. J. 1992, *ARA&A*, 30, 575
- Crocker, R. 2013, in *Astrophysics and Space Science Proceedings*, Vol. 34, *Cosmic Rays in Star-Forming Environments*, ed. D. F. Torres & O. Reimer, 397
- Crocker, R. M., Jones, D. I., Aharonian, F., Law, C. J., Melia, F., Oka, T., & Ott, J. 2011, *MNRAS*, 413, 763
- Crovisier, J., & Dickey, J. M. 1983, *A&A*, 122, 282
- Crutcher, R. M. 1999, *ApJ*, 520, 706
- . 2012, *ARA&A*, 50, 29
- Dickinson, C., Beck, R., Crocker, R., Crutcher, R. M., Davies, R. D., Ferrière, K., Fuller, G., Jaffe, T. R., Jones, D., Leahy, P., Murphy, E., Peel, M. W., Orlando, E., Porter, T., Protheroe, R. J., Strong, A., Robishaw, T., Watson, R. A., & Yusef-Zadeh, F. 2015, *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, 102
- Dobbs, C. L., Theis, C., Pringle, J. E., & Bate, M. R. 2010, *MNRAS*, 403, 625
- Drzazga, R. T., Chyży, K. T., & Jurusik, W. 2012, *ArXiv e-prints*
- Drzazga, R. T., Chyży, K. T., Jurusik, W., & Wiórkiewicz, K. 2011, *A&A*, 533, A22
- Dutta, P. 2016, *MNRAS*, 456, L117
- Dutta, P., Begum, A., Bharadwaj, S., & Chengalur, J. N. 2009, *MNRAS*, 397, L60
- . 2013, *NewA*, 19, 89
- Eatough, R. P., Falcke, H., Karuppusamy, R., Lee, K. J., Champion, D. J., Keane, E. F., Desvignes, G., Schnitzeler, D. H. F. M., Spitler, L. G., Kramer, M., Klein, B., Bassa, C., Bower, G. C., Brunthaler, A., Cognard, I., Deller, A. T., Demorest, P. B., Freire, P. C. C., Kraus, A., Lyne, A. G., Noutsos, A., Stappers, B., & Wex, N. 2013, *Nature*, 501, 391

- Elmegreen, B. G., & Scalo, J. 2004, *ARA&A*, 42, 211
- Everett, J. E., Zweibel, E. G., Benjamin, R. A., McCammon, D., Rocks, L., & Gallagher, III, J. S. 2008, *ApJ*, 674, 258
- Farnes, J. S., O’Sullivan, S. P., Corrigan, M. E., & Gaensler, B. M. 2014, *ApJ*, 795, 63
- Fletcher, A. 2010, in *Astronomical Society of the Pacific Conference Series*, Vol. 438, *The Dynamic Interstellar Medium: A Celebration of the Canadian Galactic Plane Survey*, ed. R. Kothes, T. L. Landecker, & A. G. Willis, 197
- Frick, P., Stepanov, R., Shukurov, A., & Sokoloff, D. 2001, *MNRAS*, 325, 649
- Gaensler, B. M., Haverkorn, M., Burkhart, B., Newton-McGee, K. J., Ekers, R. D., Lazarian, A., McClure-Griffiths, N. M., Robishaw, T., Dickey, J. M., & Green, A. J. 2011, *Nature*, 478, 214
- Genzel, R., Newman, S., Jones, T., Förster Schreiber, N. M., Shapiro, K., Genel, S., Lilly, S. J., Renzini, A., Tacconi, L. J., Bouché, N., Burkert, A., Cresci, G., Buschkamp, P., Carollo, C. M., Ceverino, D., Davies, R., Dekel, A., Eisenhauer, F., Hicks, E., Kurk, J., Lutz, D., Mancini, C., Naab, T., Peng, Y., Sternberg, A., Vergani, D., & Zamorani, G. 2011, *ApJ*, 733, 101
- Giovannini, G., Bonafede, A., Brown, S., Feretti, L., Ferrari, C., Gitti, M., Govoni, F., Murgia, M., & Vacca, V. 2015, *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, 104
- Govoni, F., & Feretti, L. 2004, *International Journal of Modern Physics D*, 13, 1549
- Govoni, F., Murgia, M., Xu, H., Li, H., Norman, M., Feretti, L., Giovannini, G., Vacca, V., Bernardi, G., Bonafede, A., Brunetti, G., Carretti, E., Colafrancesco, S., Donnert, J., Ferrari, C., Gitti, M., Iapichino, L., Johnston-Hollitt, M., Pizzo, R., & Rudnick, L. 2015, *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, 105
- Govoni, F., Murgia, M., Xu, H., Li, H., Norman, M. L., Feretti, L., Giovannini, G., & Vacca, V. 2013, *A&A*, 554, A102
- Green, D. A. 1993, *MNRAS*, 262, 327
- Guirado, J. C., Marcaide, J. M., Alberdi, A., Elosegui, P., Ratner, M. I., Shapiro, I. I., Kilger, R., Mantovani, F., Venturi, T., Rius, A., Ros, E., Trigilio, C., & Whitney, A. R. 1995, *AJ*, 110, 2586
- Hanasz, M., Wólczański, D., & Kowalik, K. 2009, *ApJ*, 706, L155
- Harvey-Smith, L., Gaensler, B. M., Kothes, R., Townsend, R., Heald, G. H., Ng, C.-Y., & Green, A. J. 2010, *ApJ*, 712, 1157
- Haverkorn, M., Akahori, T., Carretti, E., Ferrière, K., Frick, P., Gaensler, B., Heald, G., Johnston-Hollitt, M., Jones, D., Landecker, T., Mao, S. A., Noutsos, A., Oppermann, N., Reich, W., Robishaw, T., Scaife, A., Schnitzeler, D., Stepanov, R., Sun, X., & Taylor, R. 2015, *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, 96
- Haverkorn, M., Brown, J. C., Gaensler, B. M., & McClure-Griffiths, N. M. 2008, *ApJ*, 680, 362
- Haverkorn, M., Katgert, P., & de Bruyn, A. G. 2003, *A&A*, 404, 233

- Heald, G., Beck, R., de Blok, W. J. G., Dettmar, R. J., Fletcher, A., Gaensler, B., Haverkorn, M., Heesen, V., Horellou, C., Krause, M., Mao, S. A., Oppermann, N., Scaife, A., Sokoloff, D., Stil, J., Tabatabaei, F., Takahashi, K., Taylor, A. R., & Williams, A. 2015, *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, 106
- Heald, G., Braun, R., & Edmonds, R. 2009, *A&A*, 503, 409
- Heald, G. H. 2012, *ApJ*, 754, L35
- Heesen, V., Beck, R., Krause, M., & Dettmar, R.-J. 2009, *A&A*, 494, 563
- Heesen, V., Brinks, E., Leroy, A. K., Heald, G., Braun, R., Bigiel, F., & Beck, R. 2014, *AJ*, 147, 103
- Helou, G., & Bica, M. D. 1993, *ApJ*, 415, 93
- Herron, C. A., Burkhart, B., Lazarian, A., Gaensler, B. M., & McClure-Griffiths, N. M. 2016, *ApJ*, 822, 13
- Hirotani, K. 2005, *ApJ*, 619, 73
- Houde, M., Fletcher, A., Beck, R., Hildebrand, R. H., Vaillancourt, J. E., & Stil, J. M. 2013, *ApJ*, 766, 49
- Iacobelli, M., Haverkorn, M., Orrú, E., Pizzo, R. F., Anderson, J., Beck, R., Bell, M. R., Bonafede, A., Chyzy, K., Dettmar, R.-J., Enßlin, T. A., Heald, G., Horellou, C., Horneffer, A., Jurusik, W., Junklewitz, H., Kuniyoshi, M., Mulcahy, D. D., Paladino, R., Reich, W., Scaife, A., Sobey, C., Sotomayor-Beltran, C., Alexov, A., Asgekar, A., Avruch, I. M., Bell, M. E., van Bemmell, I., Bentum, M. J., Bernardi, G., Best, P., Birzan, L., Breitling, F., Broderick, J., Brouw, W. N., Brüggem, M., Butcher, H. R., Ciardi, B., Conway, J. E., de Gasperin, F., de Geus, E., Dusch, S., Eislöffel, J., Engels, D., Falcke, H., Fallows, R. A., Ferrari, C., Frieswijk, W., Garrett, M. A., Griebmeier, J., Gunst, A. W., Hamaker, J. P., Hassall, T. E., Hessels, J. W. T., Hoeft, M., Hörandel, J., Jelic, V., Karastergiou, A., Kondratiev, V. I., Koopmans, L. V. E., Kramer, M., Kuper, G., van Leeuwen, J., Macario, G., Mann, G., McKean, J. P., Munk, H., Pandey-Pommier, M., Polatidis, A. G., Röttgering, H., Schwarz, D., Sluman, J., Smirnov, O., Stappers, B. W., Steinmetz, M., Tagger, M., Tang, Y., Tasse, C., Toribio, C., Vermeulen, R., Vocks, C., Vogt, C., van Weeren, R. J., Wise, M. W., Wucknitz, O., Yatawatta, S., Zarka, P., & Zensus, A. 2013, *A&A*, 558, A72
- Iapichino, L., Schmidt, W., Niemeyer, J. C., & Merklein, J. 2011, *MNRAS*, 414, 2297
- Jansson, R., & Farrar, G. R. 2012, *ApJ*, 761, L11
- Jarvis, M., Seymour, N., Afonso, J., Best, P., Beswick, R., Heywood, I., Huynh, M., Murphy, E., Prandoni, I., Schinnerer, E., Simpson, C., Vaccari, M., & White, S. 2015, *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, 68
- Johnston-Hollitt, M., Govoni, F., Beck, R., Dehghan, S., Pratley, L., Akahori, T., Heald, G., Agudo, I., Bonafede, A., Carretti, E., Clarke, T., Colafrancesco, S., Ensslin, T. A., Feretti, L., Gaensler, B., Haverkorn, M., Mao, S. A., Oppermann, N., Rudnick, L., Scaife, A., Schnitzeler, D., Stil, J., Taylor, A. R., & Vacca, V. 2015, *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, 92

- Joung, M. K. R., & Mac Low, M.-M. 2006, *ApJ*, 653, 1266
- Kim, K. S., Lilly, S. J., Miniati, F., Bernet, M. L., Beck, R., O’Sullivan, S. P., & Gaensler, B. M. 2016, *ApJ*, 829, 133
- Kim, K.-T., Kronberg, P. P., Giovannini, G., & Venturi, T. 1989, *Nature*, 341, 720
- Konigl, A. 1981, *ApJ*, 243, 700
- Kothes, R., & Brown, J.-A. 2009, in *IAU Symposium*, Vol. 259, *Cosmic Magnetic Fields: From Planets, to Stars and Galaxies*, ed. K. G. Strassmeier, A. G. Kosovichev, & J. E. Beckman, 75–80
- Kramer, M., & Stappers, B. 2015, *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, 36
- Krause, M. 2014, *ArXiv e-prints*
- Lara, L., Alberdi, A., Marcaide, J. M., & Muxlow, T. W. B. 1994, *A&A*, 285, 393
- Law, C. J., Brentjens, M. A., & Novak, G. 2011, *ApJ*, 731, 36
- Lazarian, A., Esquivel, A., & Crutcher, R. 2012, *ApJ*, 757, 154
- Lazaryan, A. L., & Shutenkov, V. P. 1990, *Soviet Astronomy Letters*, 16, 297
- Li, H.-B., Goodman, A., Sridharan, T. K., Houde, M., Li, Z.-Y., Novak, G., & Tang, K. S. 2014, *Protostars and Planets VI*, 101
- Lobanov, A. P. 1998, *A&A*, 330, 79
- Lou, Y.-Q., & Fan, Z. 1998, *ApJ*, 493, 102
- Low, B. C. 1975a, *ApJ*, 197, 251
- . 1975b, *ApJ*, 198, 211
- Marcaide, J. M., & Shapiro, I. I. 1984, *ApJ*, 276, 56
- Marscher, A. P., & Brown, R. L. 1978, *ApJ*, 221, 588
- McKinney, J. C., Tchekhovskoy, A., & Blandford, R. D. 2012, *MNRAS*, 423, 3083
- Mestel, L., & Subramanian, K. 1991, *MNRAS*, 248, 677
- Mohan, P., Agarwal, A., Mangalam, A., Gupta, A. C., Wiita, P. J., Volvach, A. E., Aller, M. F., Aller, H. D., Gu, M. F., Lähteenmäki, A., Tornikoski, M., & Volvach, L. N. 2015, *MNRAS*, 452, 2004
- Moss, D. 1998, *MNRAS*, 297, 860
- Moss, D., Beck, R., Sokoloff, D., Stepanov, R., Krause, M., & Arshakian, T. G. 2013, *A&A*, 556, A147
- Moss, D., Shukurov, A., & Sokoloff, D. 2000, *A&A*, 358, 1142
- Moss, D., Sokoloff, D., Beck, R., & Krause, M. 2010, *A&A*, 512, A61

- Murgia, M., Helfer, T. T., Ekers, R., Blitz, L., Moscadelli, L., Wong, T., & Paladino, R. 2005, *A&A*, 437, 389
- Murphy, E. J. 2009a, *ApJ*, 706, 482
- . 2009b, *ApJ*, 706, 482
- Narayan, R., Igumenshchev, I. V., & Abramowicz, M. A. 2003, *PASJ*, 55, L69
- Niklas, S., & Beck, R. 1997, *A&A*, 320, 54
- Nota, T., & Katgert, P. 2010, *A&A*, 513, A65
- Novak, G., Chuss, D. T., Renbarger, T., Griffin, G. S., Newcomb, M. G., Peterson, J. B., Loewenstein, R. F., Pernic, D., & Dotson, J. L. 2003, *ApJ*, 583, L83
- Orlando, E., & Strong, A. 2013, *MNRAS*, 436, 2127
- Osherovich, V. A. 1982, *Sol. Phys.*, 77, 63
- O’Sullivan, S. P., Brown, S., Robishaw, T., Schnitzeler, D. H. F. M., McClure-Griffiths, N. M., Feain, I. J., Taylor, A. R., Gaensler, B. M., Landecker, T. L., Harvey-Smith, L., & Carretti, E. 2012, *MNRAS*, 421, 3300
- Otmianowska-Mazur, K., Elstner, D., Soida, M., & Urbanik, M. 2002, *A&A*, 384, 48
- Prasad, A., & Mangalam, A. 2013, in *Astronomical Society of India Conference Series*, Vol. 10, *Astronomical Society of India Conference Series*
- Prasad, A., & Mangalam, A. 2016, *ApJ*, 817, 12
- Prasad, A., Mangalam, A., & Ravindra, B. 2014, *ApJ*, 786, 81
- Quillen, A. C., Dougherty, J., Bagley, M. B., Minchev, I., & Comparetta, J. 2011, *MNRAS*, 417, 762
- Ramesh, R., Kathiravan, C., & Sastry, C. V. 2010, *ApJ*, 711, 1029
- Ray, T. P. 2009, in *Revista Mexicana de Astronomia y Astrofisica Conference Series*, Vol. 36, *Revista Mexicana de Astronomia y Astrofisica Conference Series*, 179–185
- Rodrigues, L. F. S., Shukurov, A., Fletcher, A., & Baugh, C. M. 2015, *MNRAS*, 450, 3472
- Roy, S., Pramesh Rao, A., & Subrahmanyam, R. 2008, *A&A*, 478, 435
- Roy, S., Rao, A. P., & Subrahmanyam, R. 2005, *MNRAS*, 360, 1305
- Ryu, D., Kang, H., & Biermann, P. L. 1998, *A&A*, 335, 19
- Ryu, D., Kang, H., Cho, J., & Das, S. 2008, *Science*, 320, 909
- Ryu, D., Schleicher, D. R. G., Treumann, R. A., Tsagas, C. G., & Widrow, L. M. 2012, *Space Sci. Rev.*, 166, 1
- Samui, S., Subramanian, K., & Srianand, R. 2010, *MNRAS*, 402, 2778

- Sastry, C. V. 2009, *ApJ*, 697, 1934
- Schinnerer, E., Meidt, S. E., Pety, J., Hughes, A., Colombo, D., García-Burillo, S., Schuster, K. F., Dumas, G., Dobbs, C. L., Leroy, A. K., Kramer, C., Thompson, T. A., & Regan, M. W. 2013, *ApJ*, 779, 42
- Schleicher, D. R. G., & Beck, R. 2013, *A&A*, 556, A142
- Sellwood, J. A., & Balbus, S. A. 1999, *ApJ*, 511, 660
- Shneider, C., Haverkorn, M., Fletcher, A., & Shukurov, A. 2014, *A&A*, 567, A82
- Shukurov, A. 1998, *MNRAS*, 299, L21
- . 2004, *ArXiv Astrophysics e-prints*
- Shukurov, A., & Berkhuijsen, E. M. 2003, *MNRAS*, 342, 496
- Shukurov, A., Sokoloff, D., Subramanian, K., & Brandenburg, A. 2006a, *A&A*, 448, L33
- . 2006b, *A&A*, 448, L33
- Simard-Normandin, M., & Kronberg, P. P. 1980, *ApJ*, 242, 74
- Smits, R., Tingay, S. J., Wex, N., Kramer, M., & Stappers, B. 2011, *A&A*, 528, A108
- Sokoloff, D., & Shukurov, A. 1990, *Nature*, 347, 51
- Stepanov, R., Frick, P., Shukurov, A., & Sokoloff, D. 2002, *A&A*, 391, 361
- Subramanian, K., & Brandenburg, A. 2006, *ApJ*, 648, L71
- Sun, X.-H., & Reich, W. 2010, *Research in Astronomy and Astrophysics*, 10, 1287
- Sur, S., Federrath, C., Schleicher, D. R. G., Banerjee, R., & Klessen, R. S. 2012, *MNRAS*, 423, 3148
- Sur, S., Scannapieco, E., & Ostriker, E. C. 2016, *ApJ*, 818, 28
- Sur, S., Schleicher, D. R. G., Banerjee, R., Federrath, C., & Klessen, R. S. 2010, *ApJ*, 721, L134
- Sur, S., Shukurov, A., & Subramanian, K. 2007, *MNRAS*, 377, 874
- Swinbank, A. M., Papadopoulos, P. P., Cox, P., Krips, M., Ivison, R. J., Smail, I., Thomson, A. P., Neri, R., Richard, J., & Ebeling, H. 2011, *ApJ*, 742, 11
- Tabatabaei, F. S., Schinnerer, E., Murphy, E. J., Beck, R., Groves, B., Meidt, S., Krause, M., Rix, H.-W., Sandstrom, K., Crocker, A. F., Galametz, M., Helou, G., Wilson, C. D., Kennicutt, R., Calzetti, D., Draine, B., Aniano, G., Dale, D., Dumas, G., Engelbracht, C. W., Gordon, K. D., Hinz, J., Kreckel, K., Montiel, E., & Roussel, H. 2013, *A&A*, 552, A19
- Tamburro, D., Rix, H.-W., Leroy, A. K., Mac Low, M.-M., Walter, F., Kennicutt, R. C., Brinks, E., & de Blok, W. J. G. 2009, *AJ*, 137, 4424
- Taylor, R., Agudo, I., Akahori, T., Beck, R., Gaensler, B., Heald, G., Johnston-Hollitt, M., Langer, M., Rudnick, L., Scaife, A., Schleicher, D., Stil, J., & Ryu, D. 2015, *Advancing Astrophysics with the Square Kilometre Array (AASKA14)*, 113

- Tchekhovskoy, A., Narayan, R., & McKinney, J. C. 2011, MNRAS, 418, L79
- Thompson, T. A., Quataert, E., Waxman, E., Murray, N., & Martin, C. L. 2006, ApJ, 645, 186
- Van Eck, C. L., Brown, J. C., Shukurov, A., & Fletcher, A. 2015, ApJ, 799, 35
- Van Eck, C. L., Brown, J. C., Stil, J. M., Rae, K., Mao, S. A., Gaensler, B. M., Shukurov, A., Taylor, A. R., Haverkorn, M., Kronberg, P. P., & McClure-Griffiths, N. M. 2011, ApJ, 728, 97
- Vazza, F., Brüggen, M., Gheller, C., & Wang, P. 2014, MNRAS, 445, 3706
- Vishniac, E. T., & Cho, J. 2001, ApJ, 550, 752
- Wiegert, T., Irwin, J., Miskolczi, A., Schmidt, P., Mora, S. C., Damas-Segovia, A., Stein, Y., English, J., Rand, R. J., Santistevan, I., Walterbos, R., Krause, M., Beck, R., Dettmar, R.-J., Kepley, A., Wezgowiec, M., Wang, Q. D., Heald, G., Li, J., MacGregor, S., Johnson, M., Strong, A. W., DeSouza, A., & Porter, T. A. 2015, AJ, 150, 81
- Xu, H., Govoni, F., Murgia, M., Li, H., Collins, D. C., Norman, M. L., Cen, R., Feretti, L., & Giovannini, G. 2012, ApJ, 759, 40
- Xu, Y., Kronberg, P. P., Habib, S., & Dufton, Q. W. 2006, ApJ, 637, 19
- Yusef-Zadeh, F., Wardle, M., Lis, D., Viti, S., Brogan, C., Chambers, E., Pound, M., & Rickert, M. 2013, Journal of Physical Chemistry A, 117, 9404
- Yusef-Zadeh, F., Wardle, M., & Roy, S. 2007, ApJ, 665, L123
- Zamaninasab, M., Clausen-Brown, E., Savolainen, T., & Tchekhovskoy, A. 2014, Nature, 510, 126
- Zdziarski, A. A., Sikora, M., Pjanka, P., & Tchekhovskoy, A. 2015, MNRAS, 451, 927